Renewable and Sustainable Energy Reviews 41 (2015) 695–714

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A state-of-the-art review on innovative glazing technologies

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A R T I C L E I N F O

Article history:
Received 20 March 2014
Received in revised form
26 July 2014
Accepted 30 August 2014

Keywords:
Buildings
Glazing technologies
Energy-efficient retrofitting
Energy saving

A B S T R A C T

Buildings play an important role in greenhouse gas emissions since they constitute a large proportion of the global energy demand. This dramatic scenario is usually a consequence of poor thermal insulation characteristics of building fabric. Among the elements of a typical building envelope, windows are responsible for the greatest energy loss due to their notably high overall heat transfer coefficients (*U*-values). About 60% of heat loss through the fabric of residential buildings can be attributed to the glazed areas. Windows are useful multifunctional devices for buildings which provide passive solar gain, air ventilation and also the ability to view the outside. However, they greatly dominate the heating and cooling demand of buildings in winter and summer, respectively. Conventional window technologies tend to have poor *U*-values which cause significant heat losses during the winter season and undesired heat gain in summer. Unique glazing technologies are therefore required to improve visual and thermal comfort of the occupants, whilst mitigating the energy consumption of buildings. In the present work, a comprehensive review of the latest developments in glazing technologies is presented. Currently available high performance glazing products and technologies are analyzed in detail with application examples.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.08.084
1364-0321/

1. Introduction

1.1. A growing requirement for highly thermal resistive windows

Windows are essential components of buildings which provide vision, air ventilation, passive solar gain, day-lighting and the opportunity to leave the building in extreme situations. However, they play an important role in total energy consumed in buildings due to their remarkably higher *U*-values compared to other components of building envelope [1]. For a typical building, the *U*-values of roof, floor, external walls and windows are around 0.16, 0.25, 0.30 and 2.00 W/m^2 K, respectively. Jelle et al. [2] report that the windows are responsible for about 60% of the total energy consumption of a building. Due to the significance of windows in reducing the energy demand of buildings, considerable attention at global scale is given to improving their performance.

As global energy prices continue on an increasing trend, there is a raising awareness of the energy efficiency requirement in all areas, and as discussed previously buildings are of significant relevance. In light of this, many countries invoke new building standards so to improve the fabric efficiency of their new buildings and in some cases to also improve the thermal performance of existing buildings through a process of retrofitting. The UK is one such country, which is seen that energy efficiency in both new and existing buildings as being crucial areas. For the majority of the UK regions, a program of tightening building standards is agreed up to 2016, where all new dwellings will have to attain a level where the emissions resulting from the running of the building are net zero in terms of carbon dioxide (CO_2). However the definition of zero carbon changes over the years since its conception. Part of the process of tightening the building regulations in the UK is to adopt a fabric energy efficiency standard. This is where the new building has to achieve an annual energy requirement (in terms of the energy required for heating) below a certain maximum level. As an example a detached dwelling would have to achieve a level below 46 kWh/m^2 year. It is predicted that the *U*-values of windows would have to be in the region of or lower than 1.2–1.4 W/m^2 K in order to meet the fabric energy efficiency standard [3]. Unfortunately, conventional window technologies are not able to meet such high thermal standards and this situation results in high energy consumption and consequently increases the CO_2 emissions to the atmosphere.

Globally standards differ from country to country, but the Passivhaus Standard set out by the Passivhaus Institute of Darmstadt in Germany is a methodology which albeit not necessarily legislative for the vast majority of the world provides a calculation process, which is predicated on the energy efficiency of the building. This standard requires that the building requires less than 15 kWh/m^2 year for space heating/cooling per year. In order to attain this level the building must be constructed from a fabric of the highest thermal resistance (generally with *U*-values below 0.15 W/m^{2}K). It therefore follows that the windows and doors must also be of the highest thermal performance and as such the standard requires that the installed *U*-value of these elements must be below 0.85 W/m^2 K [4]. In addition to minimizing heat loss, there is further reasoning behind the need for glazing to have such high thermal resistance and this concerns the internal surface temperature. One of the fundamental principles of the Passivhaus methodology is that of radiant asymmetry and therefore surfaces of walls, floors, ceilings windows and doors are prescribed not to fall below 17 °C. This also prevents large temperature differentials between surfaces, which would otherwise create convective currents within the room. By maintaining radiant asymmetry and reducing convective air movement the inhabitants feel much more comfortable at a lower room temperature thereby saving energy. Windows however, do not solely lose heat from the internal to the external surroundings but can also provide useful heat to the building through the process of solar gain. Commonly in Europe the coefficient used to measure the solar energy transmittance of glass is known as the '*g*-value' (also referred to as Solar Factor or Solar Heat Gain Coefficient). The Passivhaus methodology recognizes the importance of this heat input and it therefore forms an integral part of the energy demand calculation and as such there is a stipulation that *g*-value's should be in excess of 50%. Conversely the solar heat gained via glazing can be problematic, especially in the summer months and therefore the issue of overheating is also addressed within the Passivhaus calculation.

The ability to construct highly efficient buildings will only be achieved if measures are taken to decrease fabric *U*-values and incorporate efficient window technologies. Windows however do not comprise merely of the glazing component but also the frame, which has aspects of both heat transmission and air tightness to consider. In this regard, it is important to identify appropriate technologies to manufacture energy efficient windows, which will also improve the visual and thermal comfort of the occupants. In the United Kingdom, the British Fenestration Rating Council (BFRC) proposes a method called the Energy Index (EI) to assess the performance of windows. EI evaluates the performance of the complete window including the frame and gaskets as well as multiple glazing units and produces a characteristic number. Three factors are taken into account by EI: thermal transmittance (U_w), solar heat gain coefficient (g) and air leakage (l_a). U_w measures the heat loss characteristics of the windows. The solar heat gain coefficient generally ranges between 0 and 1 where 1 and 0 is referred to low shading and high shading, respectively. This coefficient range expresses how well the window prevents heat caused by illumination intensity. Finally air leakage value determines the ventilation heat loss rate of the window when it is exposed to a pressure difference of 50 kPa. BFRC provides a formula for EI using the three factors aforementioned as follows:

$$EI = 218.6g - 68.5U_w - l_a \tag{1}$$

Table 1
Window energy rating label scale by the British Fenestration Rating Council (BFRC).

BFRC window energy rating scale	Energy index (kWh/m^2/yr)
A^+	>0
A	0
B	−10 to 0
C	−20 to −10
D	−30 to −20
E	−50 to −30
F	−70 to −50
G	<-70

On the other hand, many researchers present various models to calculate the EI for particular locations in the world [5–8]. In line with a common energy rating style used for many consumer products in Europe, the BFRC set out a banding system for the EI rating of windows as illustrated in Table 1 [9,10]. This banding is known as the Window Energy Rating, where the bands are from A to G where A and G levels indicate the best and the worst situations, respectively. Any A^+ rating with a positive value indicates that the window is capable of delivering a net heat gain to the building (via solar gain) over an annualized period. The BFRC label provides a reliable way to determine the windows properties and compare window technologies and products. Novel window technologies with extremely low U-values, suitable g-values and low air leakage are required to be able to decrease the energy consumption of buildings.

1.2. Objective of the review

The research conducted in this review can be split into two parts in terms of its scope and objectives. First, a comprehensive review of existing glazing technologies is given in a thematic way for an easier understanding and comparison. For an efficient, practical and reliable assessment of each glazing technology, three main performance parameters are utilized in the review, which are basically the overall heat transfer coefficient (U-value), the solar heat gain coefficient (SHGC) and the visible transmittance (VT). In this respect, pioneer manufacturers are contacted for the latest developments on their commercial products, and the results are given in several tables within the scope of this review. These tables provide the readers with significant information concerning manufacturers, product names, performance parameters and the current status of glazing technologies.

It is unequivocal that a good review does not just compile all the literature on a topic and provide a lengthy summary to the reader, but provides added benefit. In this regard, this review also aims at providing a future outlook on glazing technologies. Several innovative solutions such as vacuum tube window, solar pond window and heat insulation solar glass developed at the University of Nottingham through the recently completed research projects are summarized with brief results. These are all recently patented technologies and provide extraordinary performance values, which let them to be used for both retrofitting of existing buildings and new-build applications. Hence, this review also aims at acquainting the readers with state-of-the-art research and development activities on glazing technologies for further works.

2. A summary of the literature on current window technologies

Heat exchange between windows and occupants takes place in three ways: long-wave heat exchange between the human body and the window inside surface, short wave (solar) radiation which penetrates through window glass and falls on the human body [11–14], and drafts induced by cold air drainage off the window surface [15]. Although windows are not the main element in determining human thermal comfort, their influence becomes increasingly significant when their inside surfaces are very hot or cold, the building occupant is very close to the window, or when solar radiation passing through the window is very high. Thermal comfort indices are described in ISO 7730 [16]. Predicted Mean Vote (PMV) is defined as the mean response of the large group of people to a thermal environment. This index varies on a seven-point scale $+3$ (very hot) to -3 (very cold). Predicted percentage of dissatisfaction (PPD) is defined as the percentage of the people not satisfied with the thermal environment. When the PMV values lies in the range of ± 0.5, the PPD values are 10% or less and it ensures thermal comfort of the occupants. The significant parameter to calculate the PMV is the mean radiant temperature which is defined as the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual enclosure [17].

Windows play a significant role in determining the heating and cooling load of a building, particularly when their overall area is large. As discussed previously, there are several parameters associated with the window energy balance; thermal transmittance (U-value, which determines the heat transfer between indoor and outdoor environment due to temperature difference), air leakage and g-value. The g-value is an important parameter and is determined by the solar transmittance of the window and the solar energy absorbed by the window material and reemitted inwards. Glazing manufacturers provide g-value at normal incidence only while its value at other oblique angles is required most of the time. Fresnel equations are used to determine g-values at any angle of incidence but that is a challenging and time-consuming process. To be able to utilize these equations, spectral optical constants of all the coatings and substrate are required, and this data is not available most of the time. Measuring g-value at oblique angles is also not as simple as the required set-up is very costly and usually unavailable. The g-value can be measured by calorimetric method but this facility is also rather limited. This necessitates the development of some empirical relations to determine the g-value at oblique angles. In order to do this, it is necessary to know the number of panes in a glazed unit, types and thicknesses of different coatings and substrate material as reported by several researchers [18–21].

Schultz and Svendsen [22], Montecchi and Polato [23] and Roos [24] develop empirical relations for the g-value. Schultz and Svendsen [22] successfully obtain the relation in Eq. (2) where g_o is the g-value at normal incidence which needs to be known and θ is the angle of incidence. The exponent x is nearly 4 for most of the glazings but it is expected to have somewhat different values for different glazings.

$$g = g_o\left[1-\tan^x\left(\frac{\theta}{2}\right)\right] \tag{2}$$

Karlsson and Roos [25] develop Eq. (3) where $z=\theta/90$ and a, b and c are constants. The exponents α, β, γ also depend upon number of panes in the glazing and the categorization parameter of the window. In the absence of x value in the relation of Schultz and Svendsen [22] and the categorization parameter in the relation of Karlsson and Roos [25], it is difficult to use the aforementioned equations.

$$g = g_o\left[1-az^{\alpha}-bz^{\beta}-cz^{\gamma}\right] \tag{3}$$

The heating and cooling demand of a building depends upon internal gains such as appliances and occupants, and also external gains through the building's envelope. A significant part of the external energy is in the form of solar energy (radiation) and

thermal energy flowing through the glazed parts of the buildings. The energy performance of glazing is described in terms of thermal and optical parameters. Optical parameters like solar and visible transmittance, determine the solar and lighting energy, respectively. A simple transient model for building energy simulation is suggested by Burmeister and Keller [26]. This can also be used for window energy rating. Models using the concept of balance temperature and utilization factor are described for window energy savings by several researchers [27–29]. Numerous attempts are made worldwide to perform the energy rating and labeling of windows. Many researchers [30–33] develop energy rating equations in terms of window parameters such as thermal transmittance, solar heat gain coefficient and air leakage for their local climatic conditions.

Daylighting is a natural lighting source that provides the occupants visual comfort and pleasant indoor environment. Daylighting has best color rendering index, and hence is a quality source of light. It is achieved by the light passing through the window glazing and skylights [34,35]. Daylighting is a cost effective option to reduce the electrical energy consumption in a building [36,37]. The estimation of daylight in indoor space requires an accurate determination of availability of natural lighting source outside. This includes not just the total amount of light coming from the sky but also its way of distribution. The illumination at a point inside a room depends upon the exact sky luminance distribution at that time. The standard sky range includes overcast, clear, and partly cloudy sky [8,38]. For point to point calculation, the illumination from the natural light is expressed in terms of the daylight factor which is defined as the ratio of the internal illumination and the outside illumination on a horizontal plane (from the whole of the unobstructed sky without direct sunlight). This approach is converted to average daylight factor which indicates daylighting in a space as a whole rather than at any particular point [39–42].

Among the new constructions, fully glazed front facades are highly preferred. Mainly it is from an esthetic point of view, although it provides natural light and reduces the artificial light requirement and cooling load of the building. Most of these, so called glass-curtain walls use single or double glazed clear glass. The window areas need to be optimized in terms of energy consumption and indoor thermal environment of the building by considering different orientations [43–47]. The role of windows in heating, cooling and lighting energy demand in multi-storey buildings is significant [48]. Performance of glass curtain walls in buildings is a question of research. The energy performance of large glazed facade buildings in different countries is investigated by several workers [49–51].

3. Window design and performance parameters

There are many window designs used for domestic purposes (conservatories, skylight, bay, tilt and turn, shaped and casement) and as Fig. 1 indicates, there are many factors influencing the design and performance of these windows. This section focuses on the energy efficiency criteria of windows for residential buildings, but this is not to suggest that other factors are of lesser importance. The glass and frame of a window are highly conductive and are considered to be crucial factors in determining the overall energy efficiency. In addition, the British Fenestration Rating Council states that the following factors also remarkably affect the *U*-value of a window: type of glazing material, number of glazing layers, size of the cavity between the glazing layers, type of inert gas in the cavity between the glazing layers, design, material and type of frame and the other components. Nicholls [52] makes recommendations in order to improve the performance of windows. Thermal insulation ability of windows may increase with increasing number of layers of glazing, increasing the size of the cavity between the sheets of glass, replacing the air in the cavity with Argon or Krypton gas, changing the spacer bars, and applying a low emissivity layer to one or more panes of glass.

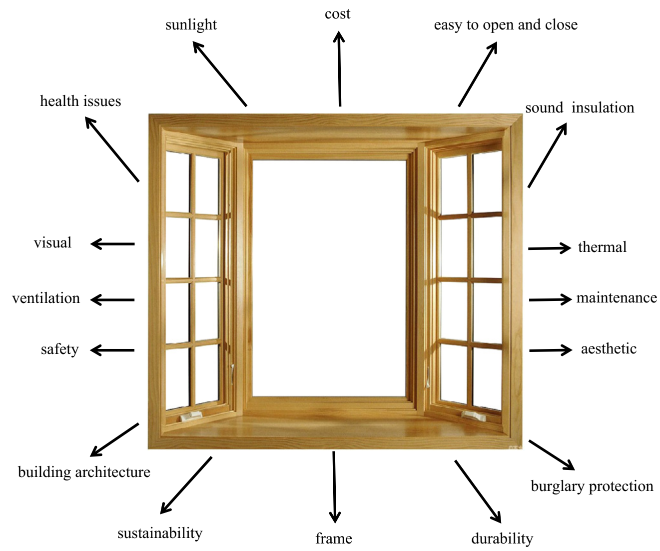


Fig. 1. Window parameters affecting the window design and performance.

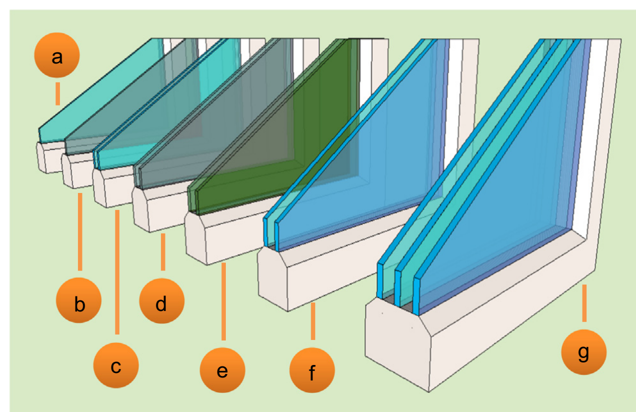


Fig. 2. Various glazing types for windows: (a) single clear glass, (b) single glazing with gray tint, (c) double clear glass, (d) double glazing with gray tint, (e) double glazing with selective tint, (f) double glazing with low-e and (g) triple glazing with low-e.

3.1. Window glazing types and energy performance

There are many types of glazing that are commonly used on residential windows as illustrated in Fig. 2. Carmody [53] investigates an annual energy performance of different glazing types using wood or vinyl frame in a typical American house in two different climates. In the analyses, he utilizes solar heat gain coefficient including the frame effects (g_{tot}), and the visible transmittance (VT). The VT is expressed as the amount of light in the visible portion of the spectrum that passes through a glazing material [54]. Visible transmittance is affected by the glazing type, the number of panes, and any glass coatings. The VT of glazing ranges from above 90% for uncoated water-white clear glass to less than 10% for highly reflective coatings on tinted glass. The results obtained from the analyses of Carmody [53] are given in Table 2. Triple low-solar-gain low-e appears to be the most energy efficient glazing system, with a *U*-value of 0.28 W/m^2 K, solar heat gain

Table 2
Performance parameters of various glazing types for windows [53].

Window	Glazing type	U-value (W/m^2 K)	SHGC	VT
A	Single, clear	0.84	0.64	0.65
B	Single, tint	0.84	0.54	0.49
C	Double, clear	0.49	0.56	0.59
D	Double, tint	0.49	0.47	0.44
E	Double, high performance tint	0.49	0.39	0.50
F	Double, high solar gain, low-e	0.37	0.53	0.54
G	Double, moderate solar gain, low-e	0.35	0.44	0.56
H	Double, low solar gain, low-e	0.34	0.30	0.51
I	Triple, moderate solar gain, low-e	0.29	0.38	0.47
J	Triple, low solar gain, low-e	0.28	0.25	0.40

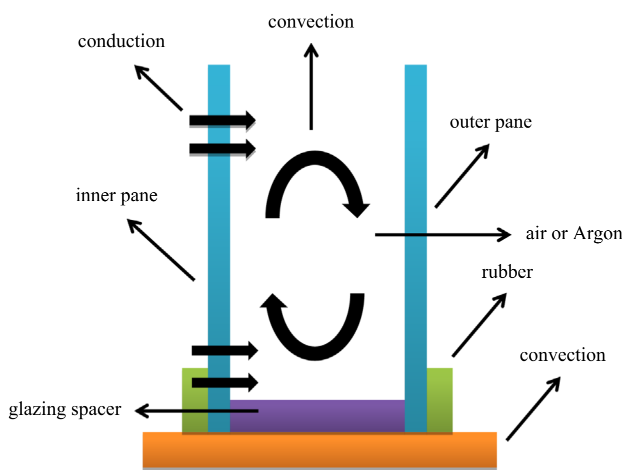


Fig. 3. Schematic of the conventional double glazed window unit.

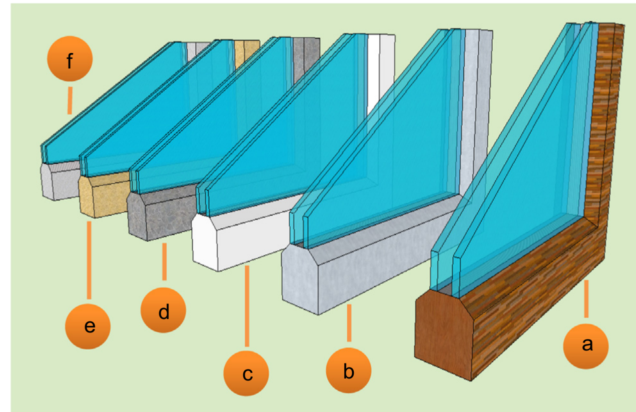


Fig. 4. Various frame types for windows: (a) wood frame, (b) aluminum frame, (c) vinyl frame, (d) clad frame, (e) hybrid frame and (f) fiberglass frame.

Table 3
Performance parameters of various frame types for windows [53].

Window	Glazing type	Frame type	U-value (W/m^2 K)	SHGC	VT
A	Double, low solar gain, low-e	Aluminum	0.59	0.37	0.59
B	Double, low solar gain, low-e	Aluminum break	0.47	0.33	0.55
C	Double, low solar gain, low-e	Wood/wood clad	0.34	0.30	0.51
D	Double, low solar gain, low-e	Vinyl	0.34	0.30	0.51
E	Double, low solar gain, low-e	Insulated fiberglass	0.26	0.31	0.55

coefficient of 0.25 and visible transmittance of 0.40. In the United Kingdom, the use of double glazed windows, a typical example of which is shown in Fig. 3, is virtually standard practice, due to their good thermal and acoustic properties. More than three sheets glass can be used but the window system then begins to become impractical due to the increased size, weight and cost.

High performance glazing concept is also investigated in the UK by Bere:architects through the project entitled 'House of the future: Comfort House' [55]. The Comfort House has no heating system, yet it remains warm in the winter and cool in summer. The house has insulation three times better than the current UK building standards. The heat from people, appliances and the sun are retained in the building to maintain a comfortable year-round temperature. In terms of the windows, the Comfort-House is fitted with super-insulated airtight frames with triple glazed windows with average U-value of 0.73 W/m^2 K.

3.2. Window frame types and energy performance

Similarly to the glazing types, there are various frame technologies as shown in Fig. 4, which are commonly used in fabrication of windows. Carmody [53] investigates the annual energy performance of a typical American house with different frame types using identical double glass, low-e type. The results indicate that the insulated fiberglass frame is the most energy efficient frame with a U-value of 0.26 W/m^2 K, solar heat gain coefficient of 0.31 and visible transmittance of 0.55. Performance assessment results of the other frames are given in Table 3. The results reveal that the non-metallic frames have better thermal characteristics than the metallic frames.

4. Global necessity of novel window technologies

Currently, the greatest share of the window market in the world is predominated by double glazing technology, and a great majority of homes that are built now have double glazing fitted as standard [56]. However, windows are still responsible for more than half of heat loss from building envelope. The ability to construct highly efficient buildings will only be achieved if measures are taken to decrease fabric U-values and incorporate efficient window technologies. Windows however do not comprise merely of the glazing component but also the frame, which has aspects of both heat transmission and air tightness to consider. In this regard, it is important to identify appropriate technologies to manufacture energy efficient windows, which will also improve the visual and thermal comfort of the occupants.

4.1. Advanced glazing types

Glazing can be considered as the most important part of fenestration products since it has a significant impact on the thermal characteristics of windows. It predominately constitutes the largest proportion of the window area and therefore the U-value of the glazing affects the overall window's U-value significantly. State-of-the-art glazing materials and technologies aim to provide high performance thermal insulation, solar gain control, daylighting solutions or a combination [57]. In the following sections, various glazing technologies are evaluated in terms of main performance parameters.

4.1.1. Multilayer glazing

Multilayer glazing can be described as the combination of glazing layers with air or a gas fill of either Argon or Krypton. The number of glazing and the inert gas type remarkably affect the thermal performance of the multilayer glazing. For instance, Krypton produces lower *U*-values with smaller cavities compared to the other inert gases as a consequence of its notably low thermal conductivity. However, its cost is considerably higher than Argon, which is the most preferred inert gas in the multilayer glazing. The multilayer glazing is currently the most commercialized glazing type in the market. Some samples of the best low *U*-value triple glazing are given in Table 4 with glazing *U*-value, visible solar transmittance and the solar factor [2]. The lowest *U*-value is found to be 0.49 W/m^2 K with a 36 mm thick configuration (4 mm glass + 12 mm Krypton + 4 mm glass + 12 mm Krypton + 4 mm glass).

Many works are conducted for the performance investigation of various multilayer glazing technologies. Han and Kim [58] prepare a multilayer film structure consisting of high/low/high (TiO_2/SiO_2/TiO_2) refractive index materials by sol–gel synthesis and spin coating process. Film thicknesses are examined by spectroscopic ellipsometry and focused ion beam techniques and refractive indices of TiO_2 and SiO_2 single layer films are also measured by spectroscopic ellipsometry. The reflectance spectra experimentally measured from multilayer films are much similar to theoretical calculations by incorporating variable refractive index into the transfer matrix. Hasan et al. [59] investigate TiO_2 and Ag based multilayer films for window glazings. The multilayer films are prepared at an elevated pressure of 3 Pa at room temperature. They are deposited and characterized by X-ray diffraction, UV–visible–NIR spectro-photometry, scanning electron microscopy and Auger electron spectroscopy. For the triple layer film of TiO_2/Ag/TiO_2, high infrared transmittance is observed. Belliot [60] develop a novel glazing provided with a stack of thin films acting on the sunlight. The multilayer is deposited by magnetron spattering which includes a lubricating film of high optical index. The lubricating film is associated with a sublayer which is based on silicon nitride or carbonitride. The invention is very appropriate for fitting into buildings to prevent the interior of rooms being excessively heated in summer and thus to minimize the cooling load of buildings. A theoretical model and experimental study are carried out by Asdrubali and Baldinelli [61] to measure the optical properties of the multilayer glazing systems. It is concluded from the study that the influence of glass thickness is nearly negligible compared to the effects of different films, which instead change significantly both the light transmittance and the external light reflectance.

Table 4
Performance parameters of various multilayer glazing types for windows [2].

Multilayer glazing type	*U*-value (W/m^2 K)	SHGC	VT
AGC GlassUK Top N$^+$	0.70	0.50	0.48
GURDIAN Flachglas Gmbh ClimaGuard N^3	0.72	0.49	0.54
GURDIAN Flachglas Gmbh ClimaGuard N	0.71	0.50	0.53
INTERPANE Glas Industrie AG Iplus 3CE	0.71	0.49	0.47
INTERPANE Glas Industrie AG Iplus 3CL	0.72	0.53	0.55

4.1.2. Suspended films

Suspended films can be considered as the artificial glass panes, which aim at increasing the thermal resistance of the window by reducing its weight. They are implemented between the outer and the inner panes, which act as an additional glass pane. Since the suspended films are very thin in comparison with the glass panes, they can provide extra thermal resistance and allow the production of multilayer glazed windows with remarkably thinner constructions. Table 5 illustrates two examples of suspended film products on the current market from Serious Materials and Visionwall Solutions Inc. Comparing these to the ordinary multilayer glazing products, suspended films have competitive *U*-values, however the challenging points of these products are the relatively low solar factor and visible solar transmittance. The suspended films are mostly equipped with low-e coatings to be able to get very low *U*-values [62]. The Visionwall product uses only air as a fill, which makes it unique. Air fill provides higher solar factor and visible solar transmittance, but it causes higher *U*-values compared to Xenon fill. The Serious Materials product uses Xenon fill, which is considerably more expensive than Argon or Krypton. However, it has a very low *U*-value of 0.28 W/m^2 K, which is in fact the lowest value among all the glazing technologies. Currently, the windows in the Empire State Building are being retrofitted by the manufacturer Serious Materials through their suspended film technology as shown in Fig. 5. This project enables to use the existing window frames and glazing as simply changing the spacers and adding in the suspended films. The project aims at reducing the energy consumption, and thus the greenhouse gas emissions significantly [63].

Another suspended film insulating glass is developed by Serious Energy Company in Canada. Suspended film packages consist of glass and films which are separated by thermally insulated spacer systems to advance the insulating performance at the edge of the glass unit. The system also contributes to reduce noise coming from outside environment. Similarly it mitigates the condensation [64]. Harrison and van Wonderen [65] employ the solar calorimetry method to evaluate the solar heat gain coefficient of more complex fenestration system such as the heat absorbing insulated glazing unit, the reflective film and suspended film insulated glazing unit with shading device. Regan et al. [66] introduce a new method to prepare suspended thin films.

4.1.3. Vacuum glazing

Vacuum glazing idea presents a low heat loss and high visible transmittance window technology [67]. The concept was first introduced in 1913 by Zoller [68,69] but was not successfully produced until 1989 [70]. The first successful fabrication of vacuum glazing was performed by Robinson and Collins [71] at the University of Sydney. The design utilized a contiguous solder glass edge seal which can be formed only at a process temperature above 450 °C. At a further stage, they elucidated this inconvenience whilst producing an edge seal vacuum glazing at below 200 °C [72–74].

A standard vacuum glazing consists of two sheets of glass separated by a narrow vacuum space with an array of support pillars keeping the two sheets of glass apart as illustrated in Fig. 6 [75]. The support pillars are often imperceptible from a particular distance, and thus their impact on vision is insignificant [76–78]. The main

Table 5
Two examples of suspended glazing from Serious Materials and Visionwall Solutions Inc. [2].

Manufacturer	Product	*U*-value (W/m^2 K)	SHGC	VT
Serious materials	1125 Picture window	0.28	0.17	0.23
Visionwall Solutions Inc.	Series 204 4-Element Glazing System	0.62	0.30	0.50

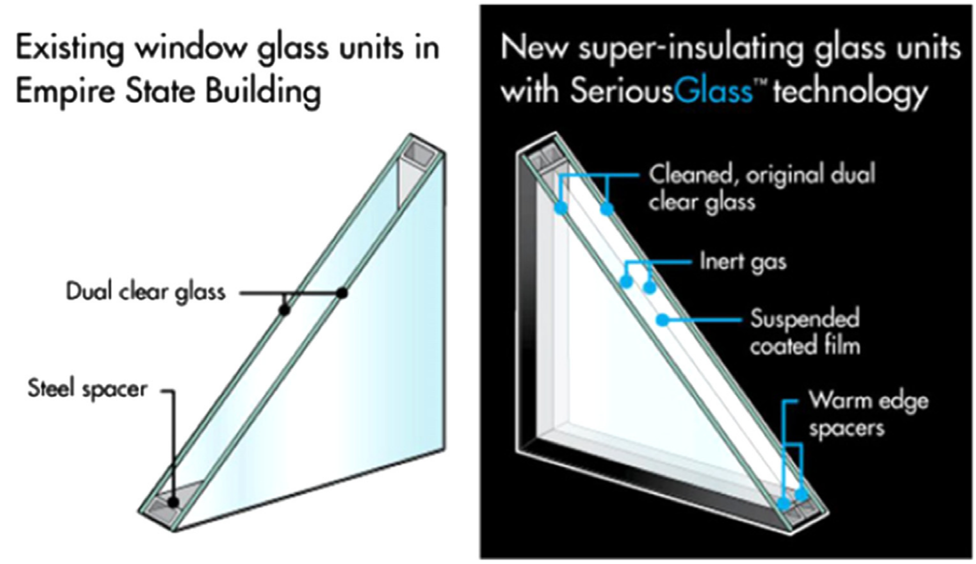


Fig. 5. Pre and post-retrofit of Empire State Building windows [63].

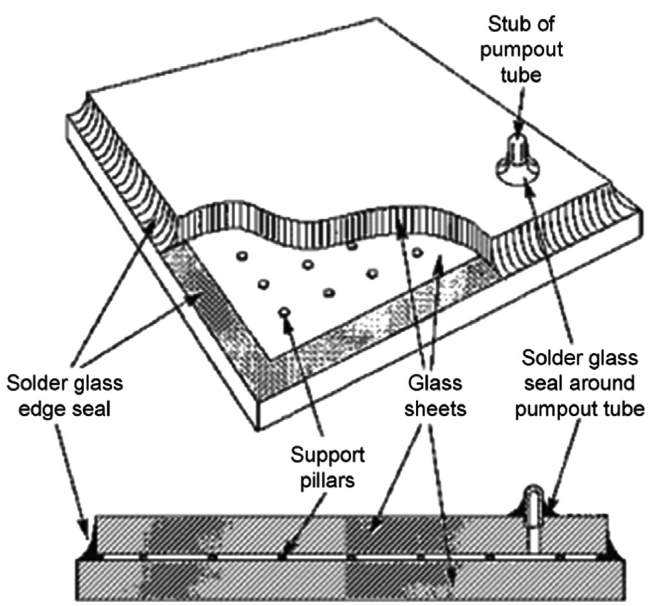


Fig. 6. Schematic of a vacuum glazing [75].

objective of the vacuum gap between the glass sheets is to eliminate the conductive and the convective heat transport.

Heat loss through radiation between the glass sheets can be reduced significantly by utilizing low-e coating as reported by Collins and Simko [79]. In this respect, Fang et al. [80] conduct a theoretical and experimental research to evaluate the thermal performance of vacuum glazing integrated with an air gap and low-e coating. Their results indicate that the *U*-value of total glazing is around 0.24 W/m^2 K with three low-e coatings. A similar *U*-value (0.20 W/m^2 K) is obtained by Manz et al. [81] by using stainless steel support pillars and four low-e coatings. Han et al. [82] investigate the thermal performance of vacuum glazing by using three-dimensional finite element method. The heat conduction through the support pillars and edge seal and the radiation between two glass sheets are evaluated. The heat conduction of residual gas in vacuum gap has been ignored for a low pressure of less than 0.1 Pa. Two pieces of vacuum glazing with sizes of 0.3 m × 0.3 m and 1.0 m × 1.0 m are simulated. In order to check the accuracy of simulations with specified mesh number, the thermal performance of a small central area (4 mm × 4 mm) with a single pillar in the center is simulated using a graded mesh of 41 × 41 × 5 nodes. The heat transfer coefficients of this unit obtained from simulation and analytic prediction are found to be 2.19 and 2.26 W/m^2 K respectively, with a deviation of 2.79%. The three dimensional (3D) isotherms and two dimensional (2D) isotherms on the cold and hot surfaces of the specimens are also presented. For the verification of simulation results, a guarded hot box calorimeter is used to determine the experimental thermal performance of 1.0 m × 1.0 m vacuum glazing. The overall heat transfer coefficients obtained from experiments and simulations are 2.55 and 2.47 W/m^2 K respectively, with a deviation of 3.14%.

Fang et al. [83] analyze thermal performance of triple vacuum glazing (TVG) which consists of three 4 mm thick glass panes with two vacuum gaps, with each internal glass surface coated with a low-e coating with an emittance of 0.03. The two vacuum gaps are sealed by an indium based sealant and separated by a stainless steel pillar array with a height of 0.12 mm and a pillar diameter of 0.3 mm spaced at 25 mm. The results show that there is a relatively large increase in the overall thermal conductance of glazing without a frame when the width of the indium edge seal is increased. Increasing the rebate depth in a solid wood frame decreases the heat transmission of the TVG. The overall heat transmission of the simulated 0.5 m × 0.5 m TVG is found to be 32.6% greater than that of the 1 m × 1 m TVG, since heat conduction through the edge seal of the small glazing has a larger contribution to the total glazing heat transfer than that of the larger glazing system. Fang et al. [84] investigate the thermal performance of vacuum glazing by using 2D finite element and 3D finite volume models. In the 2D model, the vacuum space, including the pillar arrays, is represented by a material whose effective thermal conductivity is determined from the specified vacuum space width, the heat conduction through the pillar array and the calculated radiation heat transfer between the two interior glass surfaces within the vacuum gap. In the 3D model, the support pillar array is incorporated and modeled within the glazing unit directly. The predicted difference in overall heat transfer coefficients between the two models for the vacuum window simulated is observed to be less than 3%. A guarded hot box calorimeter is utilized to determine the experimental thermal performance of vacuum glazing. The experimentally determined overall heat transfer coefficient and temperature profiles along the central line of the vacuum glazing are in very good agreement

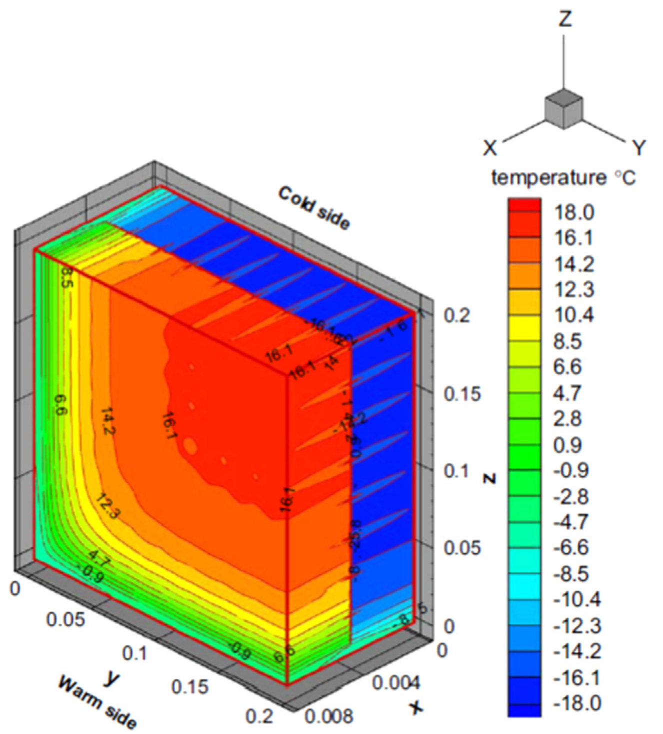


Fig. 7. Predicted 3D isotherms of vacuum glazing without frame [84].

Table 6
Thermal characteristics of SPACIA-21 vacuum glazing from Pilkington [2].

Manufacturer	Product	*U*-value (W/m^2 K)	SHGC	VT
Pilkington	SPACIA-21	0.70	0.32	0.53

with the predictions made using the 2D and 3D models. The 3D isotherms of vacuum glazing using ASTM boundary conditions are illustrated in Fig. 7. Papaefthimiou et al. [85] develop electrochromic evacuated glazing prototypes utilizing vacuum techniques and chemical methods. Their vacuum glazing aims at dynamically controlling the solar radiation penetrating into the residential buildings. The results reveal that the prototype is very promising in terms of optical and thermal performance.

If attention is paid to the fully commercialized vacuum glazing products, SPACIA-21 from Pilkington Company is seen the best vacuum glazing of the current market as also reported by Jelle et al. [2]. SPACIA-21 can be considered as a combination of evacuated and low-e coated glass sheets. The overall *U*-value of the product is around 0.70 W/m^2 K as illustrated in Table 6. This vacuum glazing is very significant for energy-efficient retrofitting of residential buildings with slimmer and lighter constructions. For instance, the external thickness of SPACIA-21 is 21 mm, whereas the thickness of a multilayer glazing like Planibel LOW-E Tri from AGC Glass UK is 40 mm for the same *U*-value.

4.1.4. Low-emittance coatings

Low-emittance coatings are basically metals or metallic oxides, and aim at allowing a great proportion of the visible light in the solar spectrum to be transmitted while blocking much of the other wavelengths responsible for undesired solar heat gain [86]. They can be split into two categories as hard and soft low-e coatings. The soft low-e coatings are less durable than the hard low-e coatings, hence require extra protective layers. However they are more transparent, and have higher infrared reflection [87–90].

Table 7
Examples of hard and soft low-e coatings currently available [2].

Manufacturer	Product	Coating	ε
Pilkington	K Glass™	Hard	0.170
Pilkington	Opitherm™ S3	Soft	0.037
Pilkington	Opitherm™ S1	Soft	0.013
Saint-Gobain Glass UK Ltd.	Planitherm Total +	Soft	0.050
Saint-Gobain Glass UK Ltd.	Planitherm Ultra N	Soft	0.030

Table 8
Electrochromic based smart windows in market [2,86].

Manufacturer	Product	*U*-value (W/m^2 K)	SHGC	VT
SAGE Electrochromics	Classic™	1.59	0.48–0.09	0.62–0.035
SAGE Electrochromics	Classic™	0.62	0.38–0.05	0.52–0.030

Recent works clearly reveal that the low-e coatings are capable of reducing heat gain through windows up to 48% [86]. Therefore they are widely used in modern architecture for thermal regulation of buildings. A significant amount of heat transport through thermal radiation can be mitigated by retrofitting existing conventional windows with low-e coatings [91].

Commercialized low-e coatings are usually classified with respect to the ratio of visible to solar transmittance. Greater values of this ratio mean cooler daylighting. The best product in this respect has a VT value of 0.66, and a SHGC value of 0.34. The theoretical limit of the concept is given by Johnson [92] as 0.66 and 0.25 for visible and thermal transmittance, respectively. Table 7 provides some low-e coatings currently available. The most challenging point of existing low-e coatings is the reduction in light transmittance, which makes the indoor environment darker [93]. Another disadvantage is their currently high cost of production.

4.1.5. Smart glazing

Smart glazing is a unique technology, which enables to change the visible and thermal transmittance characteristics to be able to obtain a desired level of lighting or heating from solar energy [94]. Smart windows can be split into three categories as chromic materials, liquid crystals and suspended particle devices. To be able to control the optical properties of smart windows, it is required to utilize chromogenic materials as reported by Granquist [95]. Chromic materials based smart windows are the most reliable and up-and-coming of the three technologies as it is clear from the commercial products given in Table 8. There are two states for electrochromic windows called transparent and colored. In the transparent state, the objective is to achieve as high visible transmittance as possible to be able to maximize the daylighting penetrating into the building. On the other hand, visible transmittance needs to be as low as possible in the colored state. Similarly, solar heat gain coefficient is expected to be as high and low as possible in the transparent and colored state, respectively.

One of the most promising advantages of the electrochromic windows is the possibility of retrofitting of the existing conventional windows [96]. They have a remarkable potential to be widely implemented into existing windows and save the cost of new glass and glazing production [2]. However, it needs to be noted that the electrochromic windows are incapable of providing full control of the uncomfortable direct sunlight effects, such as disability glare and high-luminance spots [97,98]. If more attention is paid to recent works on smart windows, Rong-Hua and Yu-Chia [99] construct a smart window comprising a building-integrated photovoltaic (BIPV) panel and an all-solid-state electrochromic stack.

In the aforementioned device, the output voltage of the BIPV panel varied in accordance with the light intensity and is modulated in such a way as to generate the electrochromic stack voltage required to maintain the indoor illumination within a specified range. Two different electrochromic stacks are developed and characterized, namely one stack comprising ITO/WO_3/Ta_2O_5/ITO and one stack comprising ITO/WO_3/lithium-polymer electrolyte/ITO. It is understood from the results that the ITO/WO_3/lithium-polymer electrolyte/ITO stack has a greater absorptance. The results also reveal that the smart window incorporating an ITO/WO_3/lithium-polymer electrolyte/ITO stack with an electrolyte thickness of 1.0 μm gives an indoor illumination range of 750–1500 lx under typical climatic conditions in Taiwan. Li et al. [100] examine the opportunities of thermochromic fenestration with VO_2-based materials to be able to regulate the solar energy transmittance. Kalagi et al. [101] investigate the limitations of dual and complementary inorganic–organic electrochromic device for smart window application. The most challenging point of smart windows at the moment is their higher cost compared to the other glazing technologies.

4.1.6. *Photovoltaic glazing*

PV glazing is a novel concept for modern architecture, and has the potential of mitigating greenhouse gas emissions from buildings. Utilizing PV cells in a window construction provides shading as well as electricity production. In this respect, total glazing area is an important parameter for this type of window as underlined by Fung and Yang [102]. The technology is based on spraying a coating of silicon nanoparticles on to the window, which work as PV cells [103–105]. Former PV glazing market is based on opaque c-Si PV cells, which make them inefficient to utilize in residential buildings. Following the developments in semi-transparent a-Si PV cell technology, PV glazing products become widespread in the market as reported by Chehab [106] and Fath et al. [107]. In the production of the a-Si based PV glazing, the cells are made thin by adding a regular pattern of tiny holes. The solar transmittance of the PV glazing is adjusted by changing the area of these holes. The reduction in power output is therefore related to the visual transmittance of the PV glazing. A recent work reveals that more than 50% of the undesired solar heat gain through conventional windows in summer can be reduced via PV glazing [86].

Jelle et al. [108] present a state-of-the-art review on building integrated photovoltaic products and their future. They emphasize that the PV glazing products can be integrated in the facade, roof or in fenestration products without causing any esthetic problem. A typical application of PV glazing is shown in Fig. 8a. Zhong-Zhu et al. [109] simulate the solar power system of building vertical photovoltaic glazing. An experimental system of photovoltaic window generation is installed on the test chamber. The mathematical model of the system is developed and verified with the measured data. Photovoltaic window generation systems, used on facades of an office building located in Beijing, Shanghai and Hong Kong, are simulated, and the relationship between the electricity output and the vertical glazing azimuth are discussed. Davidsson et al. [110] examine the performance of a hybrid PV/T solar window. It is found that the building system with individual solar energy elements, i.e. thermal collector and PV modules, of the same size as the solar window, uses 1100 kWh less energy than the system with a solar window. However, the solar window system utilizes 600 kWh less energy than a system with no solar collector. The schematic of the system and its retrofit are illustrated in Fig. 8b.

Some PV glazing products currently available in the market are illustrated in Table 9. Depending on the recent developments in PV cell technology [111–115], PV glazing concept is estimated to become widespread in the upcoming future.

Fig. 8. (a) Example of PV glazing integrated to a building [108]; (b) the solar window with water cooled PV cells, tiltable reflectors and anti-reflection treated glazing (on the left), and the retrofitted residential building (on the right).

Table 9
Examples of PV glazing in market [2].

Manufacturer	Product	*U*-value (W/m^2 K)	VT
Glaswerke Arnold GmbH & Co. KG	Voltarlux-ASI-T-ISO-E	1.10	0.10
Glaswerke Arnold GmbH & Co. KG	Voltarlux- ASI-Standard	1.20	0.10

4.1.7. *Aerogel glazing*

Aerogels are regarded as one of the most promising thermal superinsulation materials for energy-efficient retrofitting of residential buildings [116–118]. The aerogel glazing products are commonly fabricated by silica aerogel; however different types can also be utilized. Silica aerogel is not a new material [119,120], but has demonstrated a remarkable development in the last few decades. Monolithic silica aerogel is an attractive porous material, which has pore diameters in the range of 10–100 mm. Its highly porous structure combined with the nanometer pore size makes the aerogel a superinsulation material which has a thermal conductivity notably lower than still air [121]. Extraordinary optical and thermal characteristics of aerogel enable it to be utilized as insulation layers in windows. Compared to other high performance insulating glazing technologies, aerogel glazing has greater solar thermal transmittance, which plays an important role on annual energy consumption for space heating in cold climates [122]. Aerogel has very low tensile strength, which makes the material fragile. If aerogels get contact with water, the surface tension in the pores might demolish the aerogel structure. Therefore the application of aerogel glazing requires the aerogel to be protected against water and tensile stress [86].

In literature, several attempts are made for commercialization purposes of aerogel glazing. Schultz et al. [122] carry out an EU project on super insulating glazing based on monolithic silica

aerogel. Prototypes measuring roughly $55 \times 55\ cm^2$ are made with 15 mm evacuated aerogel between two layers of low-iron glass. Thus, anti-reflective treatment of the glass and a heat-treatment of the aerogel increase visible quality and solar energy transmittance. A center heat loss coefficient of the prototypes is found to be below $0.70\ W/m^2\ K$ and solar transmittance of 76%. A granular aerogel based window is developed by ZAE Bayern in Germany [123–125]. Granular silica aerogels are integrated into highly-insulating translucent glazing. To avoid settlement of the granules, which often occurred in earlier glazing concepts and even caused destruction of the glazing, the granules are sandwiched between a double skin sheet made of polymethyl-methacrylate (PMMA). The sheet is mounted between two low-e coated glass panes. To optimize the thermal insulation, Krypton is used as filling gas. This construction allows achieving heat transfer coefficients of less than $0.40\ W/m^2\ K$. Optimized granular layers provide high solar transmittance of 65% for thicknesses of 20 mm. Reim et al. [125] use two types of granular aerogel in prototype windows with a solar transmittance of 0.53 and 0.88, respectively. The aerogel glazing is integrated into facades and found to be a visually attractive, light-scattering daylight element with extremely low energy loss during the heating period. Evacuated solar collector augmented with aerogel granules, integration of the collector in the facade of the ZAE building in Wurzburg and aerogel glazing window are illustrated in Fig. 9a, b and c, respectively.

Jensen et al. [126] carry out an EU project and develop a monolithic aerogel-based window. This window is developed in combination with the technology of vacuum glazing by applying a pressure between 1 and 10 mbar. An overall heat loss coefficient of $0.66\ W/m^2\ K$ and solar thermal transmittance of more than 0.85 are measured for an evacuated glazing with 13.5 mm thick aerogel, while the noise reduction of the glazing is determined to be 33 dB. The results reveal that an energy saving of 1180 kWh/year (19%) is achieved by exchanging triple-layered argon-filled glazing with aerogel glazing in a typical new built single family house in climate conditions of Denmark [127]. An aerogel ambient drying process is developed by Kim and Hyun [128] in order to synthesize window glazing coated with silica aerogel films. The silica aerogel films are synthesized at a temperature of 270 °C and a pressure 1 atm. Thus, the transmittance of window glazing is over 90% which is more than 12% higher than that of an uncoated glass slide. The thermal conductivity of aerogel-window glazing decreases as aerogel film thickness increases. Duer and Svendsen [129] examine a number of different aerogels for their optical and thermal performance. High thermal resistance of aerogel is found for all the investigated samples and the samples show very high solar as well as light transmittance. However all of the samples tend to scatter the transmitted light, resulting in a reduced optical quality when the aerogels are integrated in glazing.

Integration of aerogel into glazing systems started to appear on the market in 2005 [130]. Buratti and Moretti [131–135] perform several experimental works on aerogel glazing systems. The main goal of their works is to investigate the optical and thermal properties of advanced glazing systems with aerogel in order to evaluate their possible employing in buildings for energy savings. They investigate both monolithic and granular aerogel glazings as illustrated in Fig. 10. The most promising of the investigated materials is found to be the monolithic aerogel, because of the better light transmittance (0.62) together with very low *U*-values (about $0.60\ W/m^2\ K$ in a double glazing with evacuated conditions), lower thickness (14 mm) and high lightness. On the other hand, for the granular systems the light reduction is about 60% if compared to a double glazing with a low-e layer; the *U*-value is little higher than $1.00\ W/m^2\ K$ with the same total thickness [132]. The results also indicate that the monolithic aerogel innovative glazing systems allow to obtain thin windows with *U*-values lower than $0.50\ W/m^2\ K$, without diminishing the solar factor or reducing considerably the daylight transmittance.

4.1.8. PCM glazing

Phase change materials (PCMs) are of prime interest especially in recent years for reducing energy consumption of buildings via thermal regulation of the building envelope. PCMs change phase from solid state to liquid as absorbing energy from the heat source. When the temperature drops, this time liquid state turns into solid state by releasing its previously stored energy. This characteristic feature of PCMs enables them to be also used in windows for energy saving purposes. Among the various types of PCMs, paraffin is more common as a consequence of its low cost. However, its low thermal conductivity [136] and large volume change during phase transition [137] are the challenging points which limit their applications in buildings. Various review works are conducted to date on PCMs and their potential applications including fenestration products [138–140].

Ismail et al. carry out several studies on PCM filled fenestration systems [141,142]. Manz et al. [143] devise and construct an external wall system for solar space heating and daylighting composed of transparent insulation material and translucent PCM. This system enables selective optical transmittance of solar radiation. Visible light is mainly transmitted and invisible radiation is mainly absorbed and converted to heat, causing in particular phase change. The storage medium is also the absorber. The concept of the system is presented in detail together with the investigations carried out, including a brief outline of modeling, optical experiments on PCM samples and long-term experiments on a prototype wall as well as numerical simulations. The results indicate a promising thermal–optical behavior of the system. The cross-section and the prototype of the system are shown in Fig. 11a and b, respectively.

GlassX Company produces a PCM glazing product called GlassX Crystal [144]. The report indicates that the *U*-value of the PCM glazing is lower than $0.50\ W/m^2\ K$. The phase change in the product is clearly seen in Fig. 12.

4.1.9. Gas filled glazing

Gas filled glazing is the most common concept of the current fenestration technologies. The gap between the glass panes is filled with a gas, which is usually air since it is the cheapest gas. However, thermal conductivity of air is 0.026 W/mK at room temperature and atmospheric pressure, which is remarkably higher than the alternative gases such as Argon and Krypton. Noble gases have very promising thermal properties. For instance, Argon, Krypton and Xenon have thermal conductivity of 0.018, 0.0095 and 0.0055 W/mK, respectively. The cost of Krypton and Xenon is considerably higher than Argon. As a consequence of this, the fenestration technology is expected to be dominated by Argon filled glazing in the upcoming future as also reported by Jelle et al. [2].

4.1.10. Self-cleaning glazing

The concept of self-cleaning glazing was first introduced Watanabe et al. [145] in 1992 on a titania-coated ceramic tile. The TiO_2 surface can decompose organic contamination with the aid of ultraviolet light. This concept has been used for many years in the covers of highway tunnel lamps in Japan [86]. The ratio of decontamination to contamination is crucial for the efficiency of self-cleaning glazing. The TiO_2 photocatalyst can provide the surface clean only if the photocatalytic decontamination rate is higher than that of contamination. As previously notified by Wang [146], the self-cleaning efficacy of TiO_2 surface can be improved by natural water flow due to the superhydrophilic property of TiO_2 surface. Similarly to Wang [146], Fujishima et al. [147] report that

Fig. 9. (a) Cross-section view of an evacuated solar collector filled with aerogel granules [124]; (b) aerogel glazing integrated in the facade of the ZAE building in Wurzburg [124]; (c) cross-section through the aerogel-glazing consisting of two glass panes [124].

the best use of self-cleaning TiO_2 surfaces need to be exterior construction materials, since these materials could be exposed to abundant solar intensity and natural rainfall. Self-cleaning products covering tiles, glass, plastic films, tent materials, cement, etc. have already been commercialized and fabricated in Japan since the late 1990s and in other countries in recent years [148,149]. Self-cleaning glazing products can be combined with anti-reflection coatings to produce multifunctional coatings [150]. They can also be integrated into energy-efficient triple glazing, vacuum glazing and aerogel products as the film is on the outer glass pane [2]. Some examples of self-cleaning glazing currently available in market are given in Table 10.

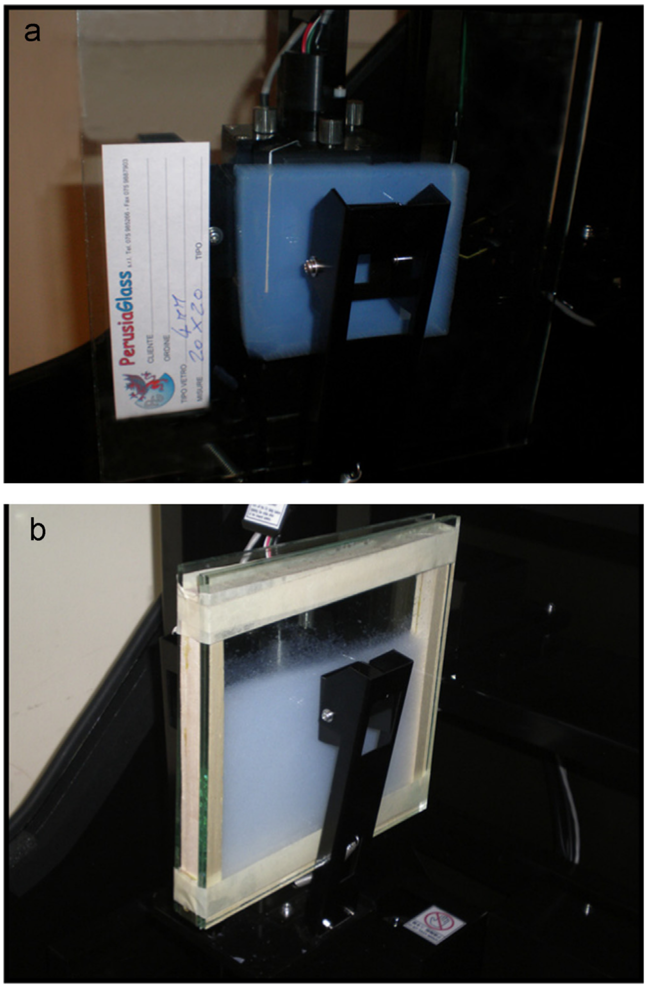


Fig. 10. (a) Monolithic aerogel and (b) granular aerogel glazings [132].

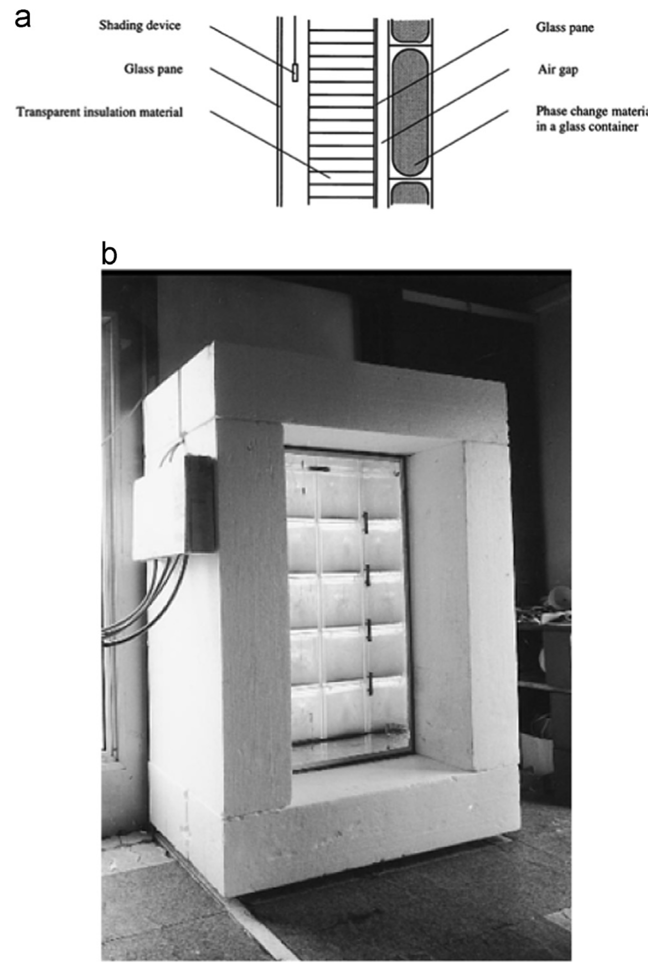


Fig. 11. (a) Cross-section of the PCM filled glazing unit [143]; (b) prototype of the PCM filled glazing unit [143].

4.2. Innovative solutions for window technologies

As it is previously clarified that each glazing technology has some particular advantages and disadvantages depending on its thermal transmittance, visible transmittance, cost, vision, cleaning, maintenance etc. In this respect, alternative solutions are utilized to develop multifunctional windows which are basically a combination of different glazing concepts. Especially under extreme weather conditions, additional measures are required to mitigate the heat loss through windows. If the hot climatic regions are considered, it is crucial to minimize the infrared portion of the solar transmission to be able to achieve lower heat gain through windows [151]. Ismail et al. [152] conduct a theoretical research on thermal performance evaluation of three different glazing technologies for hot climates. They observe that the double glass window filled with absorbing gas and absorbing glass sheets is the most effective one among the three types.

4.2.1. Solar absorbing window

The concept of solar absorbing window was first introduced by Chow et al. [151]. The system that they developed is based on the idea of removing the absorbed heat inside the cavity of the window via water flow from a feed water tank as illustrated in Fig. 13. Their simulation results indicate that the water flow in the system can efficiently decrease the glass pane temperatures, lower room heat gain, and thus the electricity consumption due to air-conditioning.

4.2.2. Reversible window

Reversible windows are mostly the double glazed windows of which the exterior surfaces are integrated with highly reflective coatings. Having low solar heat gain coefficients enable them to be used efficiently in the summer time. They are reversed in the winter time in order to collect much of the beneficial solar radiation, however winter performance of these windows are somewhat lower than the summer performance [153].

4.2.3. Switchable electrochromic window

The concept of switchable electrochromic window is based on nano-thick switchable coating on glass pane to be able to change the tint without loss of view. Lee and Tavil [154] investigate the energy and visual comfort performance of switchable electrochromic windows. In hot and cold climates such as Houston and Chicago, they observe that the switchable electrochromic windows can remarkably reduce the average annual daylight glare index and provide a significant amount of annual energy saving if the window area is large. They also notify that the energy and peak demand reductions can be notably higher if the reference window does not have exterior shading or state-of-the-art static glass.

4.2.4. Transparent insulation material filled window

The utilization of transparent insulation materials (TIMs) in building elements to reduce energy consumption with minimal

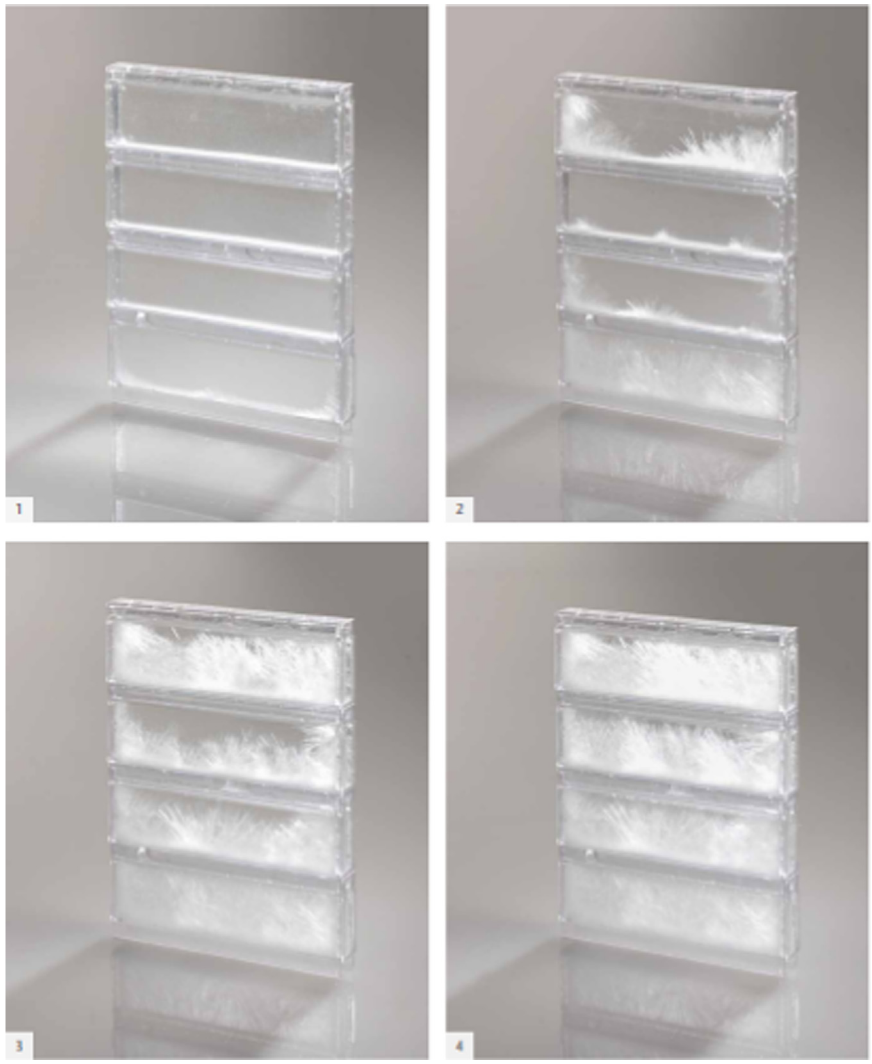


Fig. 12. Phase change in GlassX Crystal PCM glazing [144].

Table 10
Self-cleaning glazing products from current market [86].

Manufacturer	Product	U-value (W/m^2 K)	SHGC	VT
Pilkington	Pilkington Activ	1.20	0.67	0.44
Saint Gobain Glass UK Ltd.	SSG Bioclean	1.20	0.67	0.77

loss to light transmission was introduced in the 1960s [155]. TIM glazing typically consists of glass or plastic capillaries or honeycomb structures sandwiched between two glass panes. These systems diffuse light well, while notably reducing glare and shadowing [156]. The thermal performance of TIM filled windows can be considered promising. The U-values of commercial products such as Okalux are around 1.3 W/m^2 K with a 40 mm-thick. The performance is better for the thicker constructions. For instance, the U-value of 80 mm Okalux is around 0.8 W/m^2 K, which is very competitive compared to the other glazing technologies. The most challenging point of TIM filled windows is the restriction of clear view to the outside as reported by Robinson and Hutchins [157]. The light transmittance of honeycomb and capillary TIM glazing is 0.78 and 0.84, respectively. It is comparable with standard double glazing which has a light transmittance of 0.81 as given by Hutchins and Platzer [158].

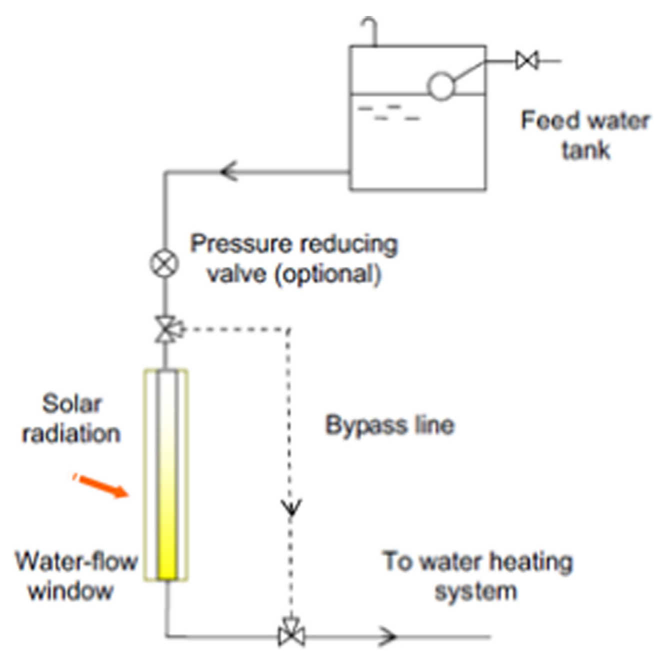


Fig. 13. The schematic of solar absorbing window [151].

4.2.5. Ventilated double glazed window

The ventilated double glazed window consists of two parallel windows forming a gap where the fresh air from outside rises as a consequence of buoyancy effects, and directed into the living space through a vent. The working principle of this window technology can be considered similar to dynamic insulation approach. Especially in winter time, the ventilated double glazed windows can operate efficiently to reduce the heating demand of buildings by preheating the incoming fresh air from outside [159].

4.3. Solar transmission controlled window

This type of window technology is especially preferred and utilized by the countries which have extremely hot climatic conditions. The concept is simply based on a window coated with a thin film which remarkably prevents solar transmission [160].

4.3.1. Tinted glazing

Tinted glazing products are fabricated by adding small metal oxides to the float or rolled glass composition. These small additions color the glass bronze, green, blue or gray but do not affect the basic properties of the glass except the solar energy transmission. The color is expected to be homogeneous throughout the thickness [161]. Tinted glazing aims at reducing not only the solar transmission but also the undesired glare. According to the results of research conducted by Chow et al. [151], thermal transmission of a room with tinted glazing can be reduced more than 20%. Further investigations indicate that light blue and green tint have higher visible performance and lower thermal transmittance among the existing products in market.

4.3.2. Reflective glazing

The concept of reflective coating is based on lowering the solar heat gain coefficient by increasing the surface reflectivity of the material [162]. Compared to the tinted glazing, reflective glazing has remarkably greater impact on reduction in solar transmission up to 50%. It is also more preferable as a consequence of its glare control and visual superiority. The microscopically thin coating on one face of the glazing provides an attractive appearance and remarkably reduces glare from direct sunlight [163].

4.3.3. Anti-reflective coated glazing

Anti-reflective coated glazing has a layer of coating on both sides to provide a clear and unobstructed view free from reflections both during the day and at night without affecting the U-value [164]. In terms of light transmittance, recent works indicate that an enhancement around 10% can be obtained through an anti-reflective coated glazing [90].

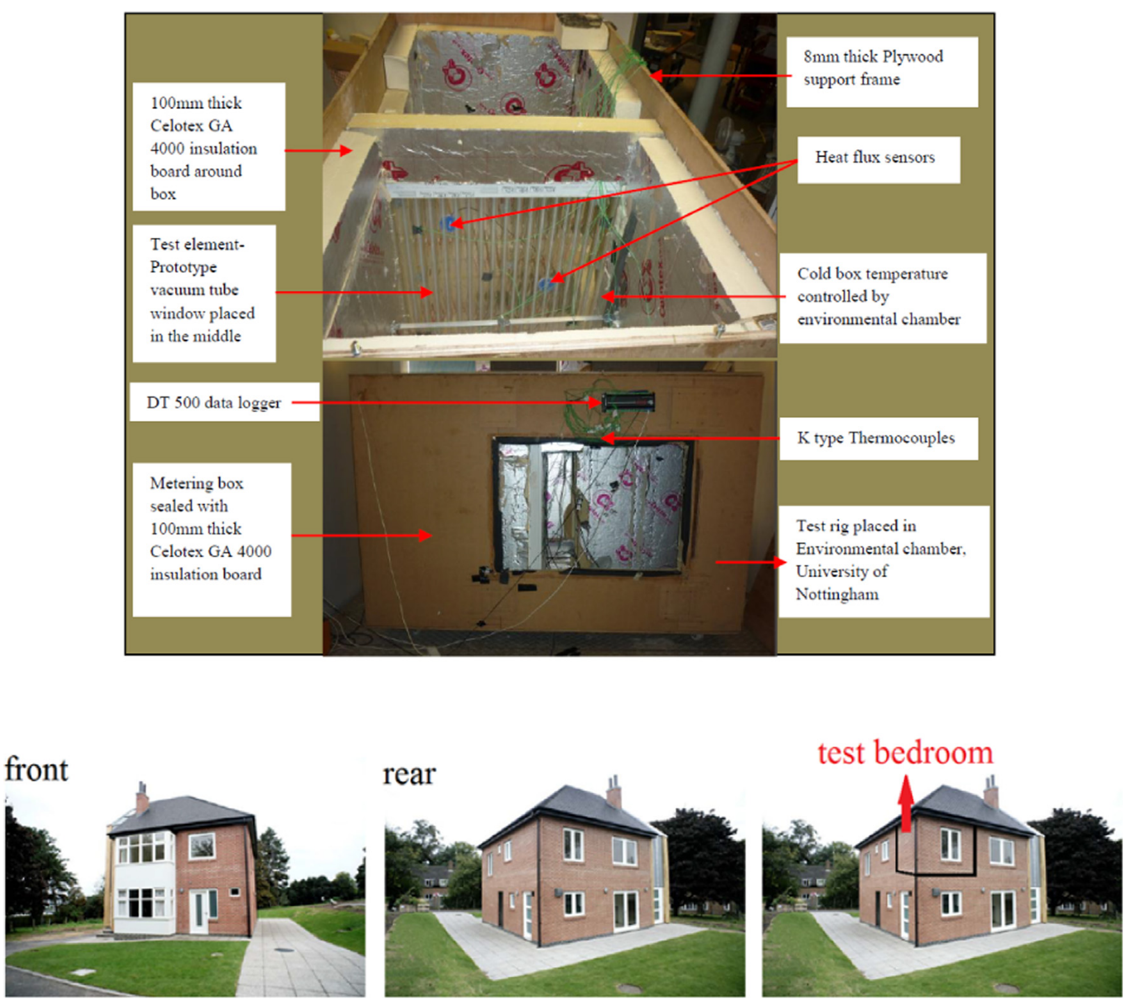
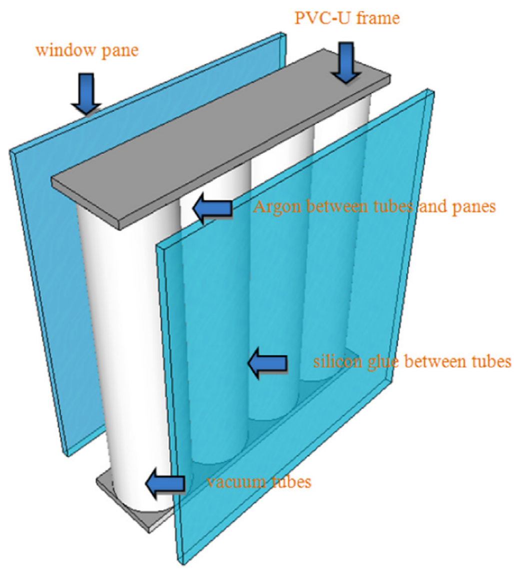
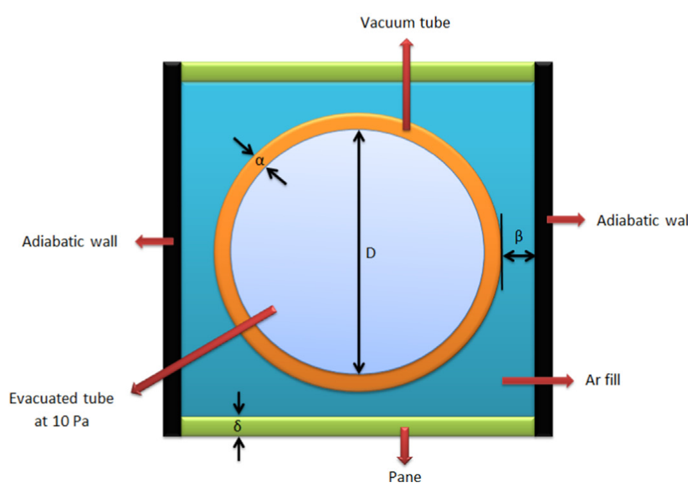


Fig. 14. The environmental chamber testing of vacuum glazing (up), and the photograph of the test house and the test bedroom utilized for the in-situ measurements (down).

5. Research on glazing technologies at the University of Nottingham

Energy-efficient retrofitting of residential buildings is an area of research which has been investigating through several EU projects [165–167] at the University of Nottingham. The retrofitting solutions also cover the innovative glazing technologies. Main interest on glazing technologies can be expressed as vacuum glazing concept. Various cost-effective configurations of vacuum glazing are analyzed both theoretically and experimentally. Experimental





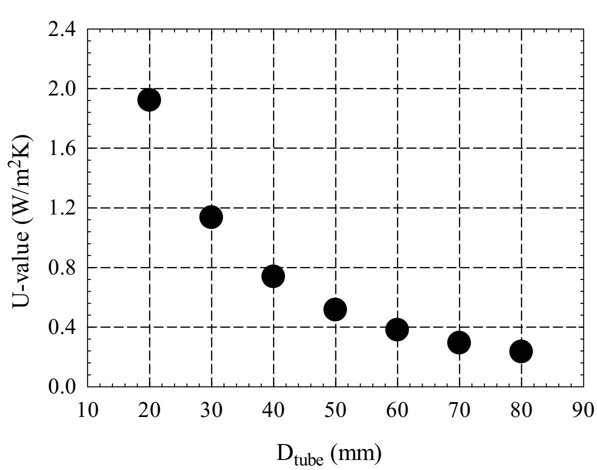


Fig. 15. 3D Schematic of novel vacuum tube glazing and the sample (up), cross-sectional view for dimensional optimization (middle) and the results for thermal insulation performance (down).

works are conducted in both environmental chamber and test house as illustrated in Fig. 14. A comprehensive CFD analysis is conducted to determine the vacuum pressure dependency of *U*-value of a typical vacuum glazing. The results have revealed that the threshold vacuum pressure is 0.1 Pa to be able to eliminate the conductive and convective effects, and thus to reduce the overall *U*-value remarkably. The CFD research also covers the dimensional optimization of the novel vacuum glazing as shown in Fig. 15. The theoretical *U*-value of the optimized vacuum glazing is found to be around 0.40 W/m^2 K for 70 mm thick window sample. On the other hand, it has been measured as 0.65 W/m^2 K through the environmental chamber tests. The results from each methodology are very preferable if a simple comparison is done with the multifunctional vacuum glazing products. For instance, the vacuum glazing integrated with different number of low-e coating is studied by Fang et al. [67], and the results they obtained are given in Fig. 16. The *U*-value of their vacuum glazing with one low-e coating is around 0.80 W/m^2 K for the emittance value of 0.02, which is notably poorer in thermal performance.

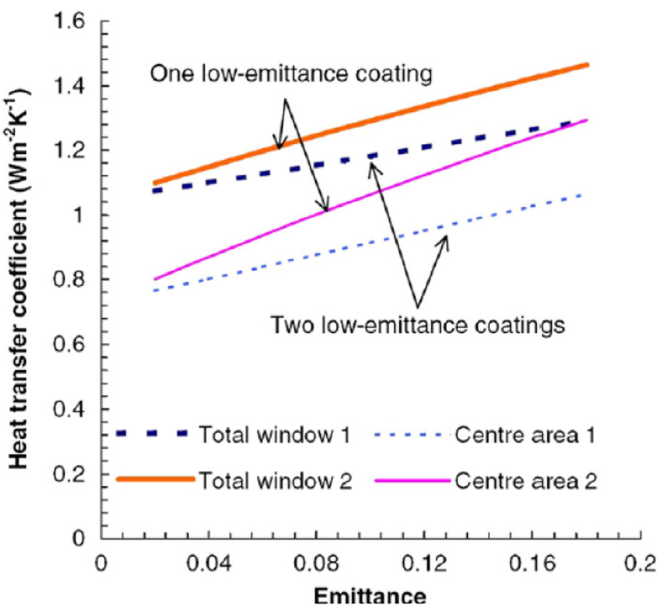


Fig. 16. Overall heat transfer coefficients of vacuum glazing window 1 with two low-e coatings and window 2 with one low-e coating [67].

Another novel glazing technology, which has been recently developed at the University of Nottingham, is solar pond window. Basically, solar pond window technology aims at providing a window with the integrated functions of lighting, heat collection, heat storage, heat preservation and photoperiod control. The novel design of solar pond window allows improving the heat collection, heat preservation, sound insulation and dust reduction effects of the architectural spaces. The schematic of the solar pond window and photograph of the sample fabricated are shown in Fig. 17. The solar pond window consists of a closed and transparent window body, which is equipped with transparent sections longitudinally inside. There are at least three completely isolated medium layers inside the solar pond window. The inner and the outer layer are filled with transparent thermal insulation liquid. The interlayer is air, water or vacuum layer. The solar pond window sample fabricated and tested at the University of Nottingham has air in the interlayer. The results indicate that the solar pond window is

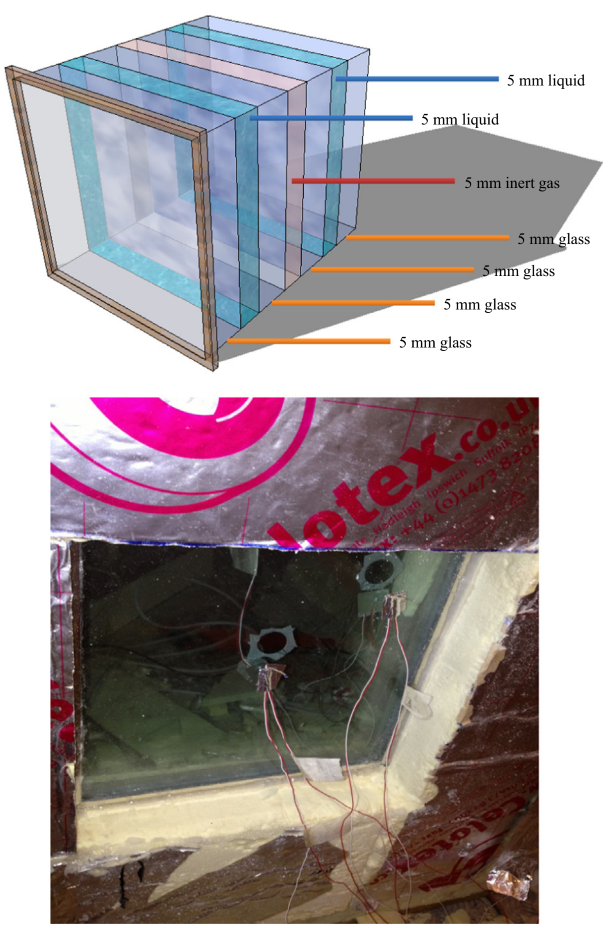


Fig. 17. Solar pond window technology developed at the University of Nottingham.

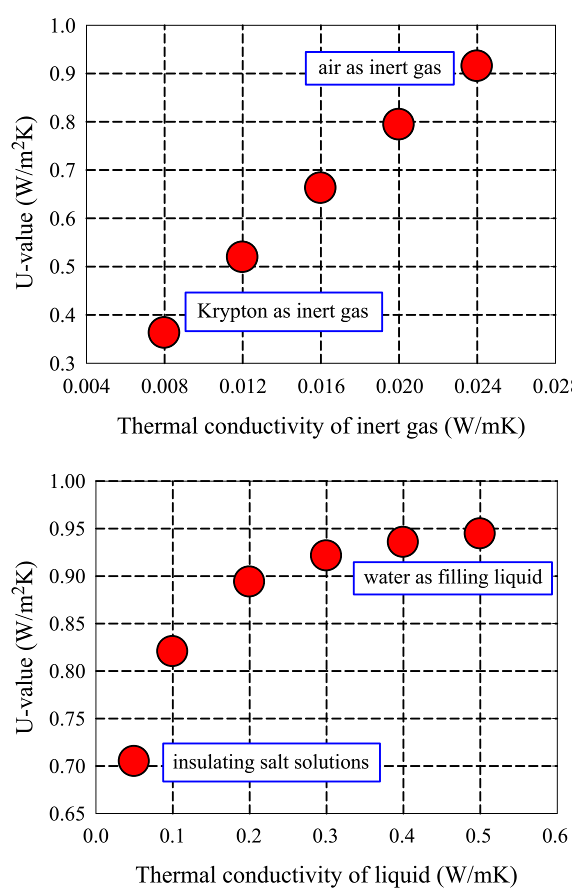


Fig. 18. Impact of the type of inert gas and liquid on the *U*-value of solar pond window.

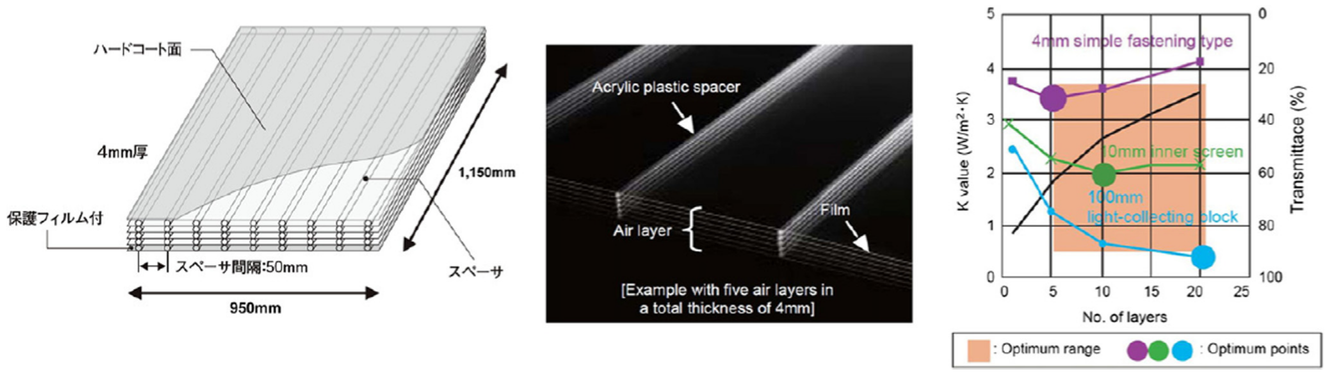


Fig. 19. The schematic of the air sandwich developed by Sekisui Company [168].

very promising for energy-efficient retrofitting of residential buildings. Through the optimized design of this novel glazing technology, the average *U*-value can be reduced below 0.40 W/m^2 K as shown in Fig. 18, which is capable of meeting the latest requirements of low-carbon buildings.

6. Prospective research on glazing technologies

Recently, Japanese Sekisui Company has introduced a unique product called *Air Sandwich*, and the research on the concept is comprehensively going on [168]. The idea is simply based on a number of thin plastic films with plastic spacers with air trapped between for insulation as illustrated in Fig. 19. The preliminary results from their product indicate that the thermal performance of the glazing greatly depends on the number of layers utilized in the structure. For instance, the *U*-value of the glazing with five air layers is 3.40 W/m^2 K, whereas it is 1.80 W/m^2 K for seven layers. While the construction changes in terms of layer, there is interestingly not a significant change in the visible transmittance of the glazing.

Another interesting idea comes from Pilkington Company for their triple glazing product NSG's SPACIA 21. In addition to the well-documented vacuum glazing concept, the product is integrated with four low-e coatings with an emittance of 0.03, resulting a *U*-value lower than 0.20 W/m^2 K. Moreover, the total thickness of the product is only 16 mm, which means slimmer and lighter retrofitting opportunities for buildings.

At the University of Nottingham, intensive efforts are made to improve the thermal and power generation performance of a miracle window called heat insulation solar glass (HISG) [169]. Latest results indicate that HISG is very appropriate for plus energy concept in buildings. Under a solar intensity of 850 W/m^2, over 40 W electrical power is obtained from HISG samples with a glazing area of 0.66 m^2. The average *U*-value of HISG is found to be 1.10 W/m^2 K, which is competitive with commercial triple glazed windows. Besides its outstanding features such as thermal insulation, sound insulation, self-cleaning and energy saving, having an ability of generating electricity enables HISG to become wide spread in the near future for both energy-efficient retrofitting of residential buildings and new-build applications.

7. Conclusions

In this study, a thorough review of the innovative glazing technologies is presented. Almost all of the works conducted so far on each glazing technology, and the state-of-the-art commercial products are evaluated in a comparative way, covering mainly thermal, visual and cost performance. The following conclusive remarks can be summarized through the work:

- Among the existing high performance fenestration technologies, double and triple glazed multilayer products constitute the majority as a consequence of their cost-effective and well-documented fabrication processes. However, vacuum glazing and aerogel glazing are expected to dominate the market in the near future as a consequence of their remarkably lower *U*-values which are around 0.30 W/m^2 K.
- Standard double glazed windows integrated with low-e coatings can provide competitive *U*-values. However, the cost remarkably increases with the number of low-e coating utilized.
- Type of inert gas plays a significant role in thermal insulation performance of glazing products. Krypton or Xenon filled glazing can be preferred in cases where the thermal performance and the practicality are more important than cost.
- For both providing a high thermal resistance and controlling the solar radiation, the combination of vacuum and aerogel glazing can be the optimum solution as reported by Jelle et al. [2]. It such an attempt, the vacuum pressure needs to be lower than 0.1 Pa if conductive and convective effects are desired to be eliminated. In addition, edge effect optimization is of vital importance in fabrication of such a glazing to be able to achieve the desired superior thermal resistance across the window.
- Vacuum tube window technology provides a *U*-value of 0.40 W/m^2 K with an entire glazing thickness of 70 mm. The most promising aspect of this novel window is its cost-effectiveness compared to other glazing products. The total cost of vacuum tube window is below 100€/m^2 whereas it is three times more expensive for standard double or triple glazed windows [170].
- Solar pond window is a cost-effective and high performance product to mitigate energy consumed in buildings. Through the dimensional optimization and appropriate selection of inert gas and insulation liquid, the average *U*-value can be reduced below 0.40 W/m^2 K.
- The frames are responsible for a great amount of heat loss through windows due to their poor thermal characteristics. The lowest frame *U*-value is currently around 0.60 W/m^2 K, which means additional measures are compulsory to be able to decrease the *U*-values of the glazing products.

Acknowledgments

We thank the financial support of the following scientific projects to this work:

1. HERB – Holistic Energy-efficient Retrofitting of Residential Buildings. EU funded Research Project, Project no: 314283, 2012–2016.
2. A High Performance Vacuum Tube Window. DECC-HPVTW Project, 2012–2014.
3. Eon Retrofit Research House Testing Phase 3.1., 2012.

We also appreciate reviewers for their significant contribution to this work and the copyright owners for the permission of using some sources in this research with proper citations.

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